Performance Evaluation of Marine Clay Subgrade Stabilized with Industrial Wastes and Reinforced Using Reclaimed Rubber Cell Mattress

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Abstract - India's expanding transportation infrastructure requires construction of pavements over weak subgrade soils such as marine clay, which exhibit low strength, high compressibility, and significant moisture sensitivity. This study evaluates the feasibility of utilizing industrial waste materials—marble dust (MD), quarry dust (QD), fly ash (FA), bagasse ash (BA), and granulated blast furnace slag (GBFS)—for subgrade and sub-base stabilization in flexible pavement systems. Laboratory investigations including Atterberg limits, Standard Proctor compaction, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and triaxial shear tests were conducted in accordance with relevant IS and IRC specifications. The optimum subgrade stabilization mixes were identified as 20% MD + 4% lime and 25% QD + 6% lime, producing increases of 143% and 460% in soaked CBR, respectively. For sub-base applications, a mix of 60% FA + 40% GBFS exhibited superior strength, stiffness, and permeability characteristics comparable to conventional granular sub-base materials. Model pavement studies performed on unreinforced, geogrid-reinforced, and reclaimed rubber cell mattress (RRCM)-reinforced sections demonstrated enhanced load-deformation behavior and significant stress reduction at the subgrade–sub-base interface. The results confirm that integrating industrial waste materials and reinforcement layers improves the structural performance and durability of pavements while promoting sustainable and cost-effective highway construction.

Key Words: Marine clay, industrial waste materials, marble dust, quarry dust, fly ash, bagasse ash, GBFS, geogrid, reclaimed rubber cell mattress, CBR, UCS, pavement stabilization.

1. INTRODUCTION

Road pavements constitute a critical component of transportation infrastructure, enabling efficient movement of passengers, goods, and essential services. The long-term performance of flexible pavements depends primarily on the engineering properties of the constituent layers, particularly the subgrade soil, sub-base, and base materials, as well as environmental conditions, construction quality, and traffic loading. Flexible pavements are preferred in developing regions due to their lower initial cost, ease of maintenance, and shorter construction periods. Rapid industrialization and population growth in India have significantly increased the demand for transportation infrastructure, leading to challenges such as scarcity of land suitable for road construction, depletion of natural aggregates, and the need for environmentally safe disposal of industrial waste. In coastal regions, the prevalence of marine clay poses additional engineering challenges due to its low shear strength, high compressibility, and sensitivity to moisture variation. As a result, such soils require stabilization before being utilized in pavement construction.

The growing traffic volume, characterized by an annual increase of 7–10% in vehicular movement and more than 12% rise in vehicle population, places considerable stress on the existing road network. This necessitates the development of improved pavement materials capable of sustaining higher axle loads and increased repetitions of wheel loading. However, the scarcity and rising cost of conventional aggregates highlight the pressing need to explore alternative, sustainable construction materials.

Industrial by-products such as marble dust, quarry dust, fly ash, bagasse ash, and granulated blast furnace slag have shown potential for enhancing soil strength through pozzolanic reaction, mechanical stabilization, or both. Simultaneously, the use of reinforcing elements such as geogrids and reclaimed rubber products offers additional improvement in load distribution and deformation control in pavement layers.

In this context, the present study investigates the stabilization of marine clay using selected industrial waste materials and the reinforcement of pavement layers using reclaimed rubber cell mattresses derived from waste tyres. The overarching objective is to develop an eco-friendly, cost-effective, and structurally superior alternative to conventional pavement construction materials while addressing the growing issue of industrial waste accumulation.

1.1 OBJECTIVES OF THE STUDY

- To evaluate the feasibility of industrial waste materials—marble dust, quarry dust, fly ash, bagasse ash, and granulated blast furnace slag—for application in pavement subgrade and sub-base stabilization.
- To characterize the physical, chemical, and engineering properties of the selected waste materials and conventional pavement materials in accordance with relevant IS and IRC standards.
- To determine optimum stabilization mixes for marine clay subgrade and industrial waste–based sub-base materials through laboratory investigations including compaction, CBR, UCS, and index property tests.
- To examine the load–deformation behavior of pavement sections incorporating waste-material-based sub-base

layers resting on unstabilized and stabilized marine clay using small-scale model pavement tests.

- To investigate the reinforcement effect of geogrid and reclaimed rubber cell mattress (RRCM) derived from waste tyres in enhancing load-carrying capacity and stress distribution within the pavement structure.
- To analyze vertical stress distribution at the subgrade–sub-base interface for reinforced and unreinforced pavement models incorporating waste materials.
- To evaluate the influence of different subgrade soils, particularly marine clay and moorum, on the performance of sub-base mixes prepared using industrial wastes.
- To compare the construction cost of conventional flexible pavements and those incorporating industrial waste–based cementitious sub-base layers using standard schedule of rates.

2. SUMMARY OF LITERATURE REVIEW

The literature review highlights extensive research on improving the engineering behavior of weak subgrade soils and enhancing pavement performance through the use of industrial waste materials and reinforcement systems. Studies on soil stabilization indicate that additives such as fly ash, lime, rice husk ash, marble dust, quarry dust, and bagasse ash significantly improve the strength, compaction characteristics, and durability of problematic soils including marine clay and expansive clays. Marble dust and quarry dust have been shown to reduce plasticity, increase dry density, and enhance CBR and UCS values due to their pozzolanic and filler effects.

Research on fly ash and GBFS emphasizes their suitability for use in sub-base and base layers, showing improvements in shear strength, CBR, and stiffness, particularly when blended with lime or cement. Bagasse ash, although less reactive alone, demonstrates improved performance when used with lime or other stabilizers. Previous works also identify slag-based mixes as cost-effective and sustainable alternatives to conventional aggregates.

Studies on waste rubber, including shredded rubber and tyre chips, reveal their potential as reinforcement elements due to their elastic properties, increasing load-bearing capacity and reducing deformation in pavement layers. Several researchers demonstrate that waste tyre–based reinforcements, such as rubber chips or rubber grids, enhance CBR and improve pavement stability.

Geosynthetics—including geogrids, geotextiles, and geocells—have been widely used as reinforcement in pavement systems. Literature confirms that these materials improve bearing capacity, reduce rutting, and minimize pavement thickness. Model tank experiments conducted by various authors show that geocells and geogrids significantly enhance load distribution under static and repeated loading conditions.

Overall, existing studies establish that industrial waste materials (fly ash, slag, marble dust, quarry dust, bagasse ash) and reinforcement systems (geogrid, geocell, rubber-based reinforcements) are effective in improving soil strength and pavement performance. However, limited research exists on the combined use of multiple industrial wastes with reclaimed rubber cell mattress systems, especially for marine clay stabilization and sub-base construction, indicating a significant gap addressed in the present study.

3. METHODOLOGY

The methodology adopted in this study consists of systematic laboratory testing, material characterization, mix design optimization, and model pavement evaluation to assess the performance of marine clay stabilized with industrial waste materials and reinforced using reclaimed rubber cell mattress (RRCM). The overall research framework is summarized below.

A. Material Collection and Characterization

1. **Marine Clay and Moorum:** Collected from identified field locations and tested for index properties, grain size distribution, compaction characteristics, and shear strength parameters.

2. **Industrial Waste Materials:** Marble dust (MD), quarry dust (QD), fly ash (FA), bagasse ash (BA), and granulated blast furnace slag (GBFS) were collected and characterized for:

- Specific gravity
- Particle size distribution
- Chemical composition
- Plasticity characteristics
- Compaction properties

3. **Reinforcement Materials:**

- Commercial geogrid
- Reclaimed Rubber Cell Mattress (RRCM) fabricated from waste tyre rubber sheets

Both evaluated for mechanical integrity and suitability for reinforcement.

B. Stabilization of Marine Clay Subgrade

1. Marine clay was blended with varying proportions of:

- MD + Lime
- QD + Lime
- Lime alone

2. For each mix proportion, the following laboratory tests were conducted:

- Standard Proctor compaction
- Atterberg limits
- Soaked and unsoaked CBR
- Unconfined Compressive Strength (UCS)
- Triaxial shear strength (U–U)
- Elastic modulus estimation

3. Optimum stabilization mixes were identified based on maximum strength and improved engineering properties.

C. Development of Sub-base Mixes Using Industrial Wastes

Two groups of sub-base mixes were prepared:

1. FA–GBFS blends
2. BA–GBFS blends

Each combination was tested for:

- Optimum moisture content (OMC)
- Maximum dry density (MDD)
- CBR (soaked/unsoaked)
- UCS
- Permeability
- Effect of curing (3, 7, 14, 28 days)

Optimum blends were selected for use in model pavement studies.

D. Model Pavement Construction and Testing

Small-scale model pavement sections were prepared in a rigid test tank with the following configurations:

1. **Unstabilized marine clay subgrade + waste-material sub-base**
2. **Stabilized marine clay subgrade + waste-material sub-base**
3. **Reinforced pavement sections:**

- Geogrid at the subgrade–sub-base interface
- RRCM reinforcement within the sub-base layer

Each model consisted of:

- Prepared subgrade
- Optimized waste-based sub-base
- Surface loading plate

Load–Deformation Testing

A static loading setup was used to measure:

- Load–settlement response
- Improvement in bearing capacity
- Deformation characteristics under incremental loads

Stress Distribution Measurement

Pressure cells were installed at the subgrade–sub-base interface to quantify:

- Vertical stress distribution
- Effectiveness of reinforcement
- Effect of stabilization on stress attenuation

E. Numerical Simulation

A limited numerical analysis was performed using **PLAXIS 2D** to validate experimental model results for:

- Unreinforced FA–GBFS sub-base
- Reinforced sub-base (geogrid / RRCM)
- Pavement resting on unstabilized marine clay

Parameters from laboratory tests were used as input for constitutive modeling.

F. Pavement Design and Cost Analysis

Using IITPAVE and IRC-37 guidelines:

1. **Mechanistic–Empirical design** was carried out for:

- Conventional pavement
- Cementitious sub-base pavement (FA–GBFS)

2. **Fatigue and rutting performance** were evaluated for each pavement configuration.

3. **Cost comparison** was made using the Public Works Department (PWD) Schedule of Rates (2020–21).

The development of sustainable pavement systems necessitates the exploration of industrial by-products and alternative materials to address challenges related to resource scarcity, environmental impact, and rising construction costs. This study utilizes several industrial waste materials—including fly ash (FA), bagasse ash (BA), granulated blast furnace slag (GBFS), marble dust (MD), quarry dust (QD)—and reinforcement systems such as geogrids and reclaimed rubber cell mattresses (RRCM). The material characteristics and their relevance to pavement engineering are summarized below.

A. Fly Ash

Fly ash is a major by-product of coal-based thermal power plants (TPPs). India produces over 130 million tonnes of fly ash annually, of which only a small fraction is utilized. Fly ash is classified as:

- **Class F:** Low-calcium fly ash with pozzolanic properties, derived from bituminous or anthracite coal.
- **Class C:** High-calcium fly ash with cementitious as well as pozzolanic characteristics, obtained from lignite or sub-bituminous coal.

The reactivity of fly ash allows it to improve soil strength through the formation of C–S–H gels when combined with lime or GBFS. Its fine particle size and low unit weight make it suitable for sub-base stabilization and embankment construction.

B. Bagasse Ash

Bagasse ash (BA) is generated from sugar industry boilers after burning sugarcane bagasse. It contains significant amounts of silica, making it a potential pozzolanic material. Although BA alone offers marginal improvement in soil strength, its performance increases when combined with lime or other cementitious binders. BA has been successfully used in low-strength pavement layers and in the stabilization of clayey soils.

C. Granulated Blast Furnace Slag

Granulated blast furnace slag (GBFS) is an industrial by-product from the steel manufacturing process. It comprises silica, alumina, and calcium oxides, enabling it to act as a latent hydraulic binder. When mixed with fly ash or BA, GBFS significantly enhances:

- Strength characteristics (UCS, CBR)
- Stiffness and modulus values
- Durability and resistance to moisture

GBFS has been recognized as a sustainable substitute for natural aggregates in pavement layers.

D. Marble Dust

Marble dust is produced during cutting and polishing of marble stones. It contains high amounts of calcium oxide (CaO), making it a viable soil stabilizer. Previous studies show that marble dust:

- Reduces plasticity and swelling of clay
- Increases maximum dry density
- Improves CBR and UCS due to pozzolanic reactions when lime is present

Its availability and low cost make it suitable for stabilizing weak subgrade soils such as marine clay.

E. Quarry Dust

Quarry dust is a by-product of aggregate crushing operations. It consists of angular, coarse-grained particles that exhibit good mechanical interlock. Quarry dust improves:

- Dry density
- Shear strength
- Load-bearing capacity

Due to its granular nature, QD is widely used as a replacement for sand and as a stabilizing agent for clayey subgrade soils when combined with lime.

F. Rubber Waste and Reclaimed Rubber

Rubber waste, particularly from discarded tyres, presents a growing environmental challenge. Reclaimed rubber is produced through mechanical or chemical processes that break down vulcanized rubber into reusable form. Reclaimed tyre products exhibit:

- High elasticity
- Good tensile strength
- Resistance to deformation

These properties make rubber suitable for reinforcement applications in geotechnical structures.

G. Reclaimed Rubber Cell Mattress (RRCM)

The RRCM system is fabricated from reclaimed tyre rubber sheets. It functions similarly to geocells by confining the infill material, thereby improving:

- Load distribution
- Lateral confinement
- Reduction of vertical stresses at the subgrade–sub-base interface

Using waste rubber in pavement systems provides both environmental and structural benefits.

H. Geogrid Reinforcement

Geogrids are widely used polymeric reinforcement elements in pavements. Their inclusion:

- Enhances tensile resistance
- Improves load transfer
- Reduces rutting and deformation

Geogrids placed at the subgrade–sub-base interface or within the sub-base layer significantly improve pavement performance, particularly over weak subgrade soils such as marine clay.

Table-1: Ash generation in India with Coal Consumptions (Ref.: NPTC 2010-11)

Year	Thermal power generation	Coal consumption	Ash generation
1995	54,000 MW	200 MT	75 MT
2000	70,000 MW	250 MT	90 MT
2010	98,000 MW	300 MT	131 MT
2020	137,000 MW	350 MT	140 MT

Table-2: Ash generation and land requirement for disposal of ash (Ref.: NPTC 2010-11)

Ash (%)	Raw coal requirements (Million Tonne per Annum)	Ash generated Million Tonne per Annum	Land requirement
41	3.77 MTPA	1.55 MTPA	400 (Ha)
36	3.33 MTPA	1.20 MTPA	310 (Ha)
34	3.19 MTPA	1.09 MTPA	281 (Ha)
32	3.07 MTPA	0.98 MTPA	254 (Ha)
30	2.97 MTPA	0.89 MTPA	229 (Ha)

4. EXPERIMENTAL INVESTIGATION

A. Material Characterisation

1) Subgrade Soils (Marine Clay and Moorum)

Marine clay and moorum were collected from designated field locations. The samples were oven-dried, pulverized, and tested as per IS:2720 standards. Characterisation included:

- Specific gravity
- Particle size distribution
- Atterberg limits
- Standard Proctor compaction
- Unconfined compressive strength (UCS)
- California Bearing Ratio (CBR)
- Shear strength parameters (from U–U triaxial tests)

Marine clay exhibited high plasticity and low shear strength, while moorum showed non-plastic, granular characteristics suitable for use as a subgrade/sub-base layer.

2) Industrial Waste Materials

The following industrial wastes were collected and examined for their engineering suitability:

- Fly Ash (FA): Class F fly ash obtained from a thermal power plant.
- Bagasse Ash (BA): Collected from sugar mill boilers.
- Granulated Blast Furnace Slag (GBFS): Procured from a steel plant.
- Marble Dust (MD): Generated from marble cutting and polishing units.

- Quarry Dust (QD): Obtained from aggregate crushing facilities.

Tests Conducted

Each material was subjected to:

- Specific gravity
- Grain size analysis
- Chemical composition (CaO, SiO_2, Al_2O_3)
- Moisture–density characteristics (Proctor compaction)
- CBR and UCS (where required)

Pozzolanic potential was assessed through CaO percentage and fineness.

3) Reinforcement Materials

a) Geogrid

A commercial biaxial geogrid with high tensile stiffness was used. Characterisation included:

- Aperture size
- Tensile strength
- Junction efficiency
- Rib thickness

b) Reclaimed Rubber Cell Mattress (RRCM)

RRCM was fabricated from reclaimed waste tyre rubber sheets. Properties evaluated:

- Thickness and cell geometry
- Tensile resistance
- Flexural rigidity
- Durability characteristics

RRCM was selected due to its large confinement capacity and sustainable waste reuse potential.

B. Experimental Programme

The experimental programme comprised two major stages:

1. Soil stabilization and sub-base mix evaluation
2. Model pavement construction and testing

C. Subgrade Stabilization Procedure

Marine clay was stabilized using various combinations of industrial wastes:

- MD + Lime
- QD + Lime
- Lime alone

Mixing was performed using dry mixing followed by addition of optimum water content. The stabilized specimens were tested for:

- Compaction characteristics
- Atterberg limits
- UCS (at 3, 7, and 14 days curing)
- CBR (soaked and unsoaked)
- Shear strength (triaxial U–U)
- Modulus estimation

Optimum mixes were identified based on improvements in CBR, UCS, and reduction in plasticity.

D. Preparation and Testing of Sub-base Mixes

Two categories of sub-base mixes were developed:

1. FA–GBFS blends
2. BA–GBFS blends

Each mix underwent:

- Standard Proctor compaction
- CBR testing
- UCS testing (with 3–28 days curing)
- Permeability testing
- Moisture sensitivity analysis

Optimum sub-base compositions were selected for model pavement evaluation.

E. Model Pavement Experimental Set-Up

A rigid steel test tank was used to construct small-scale pavement models with the following configurations:

1. Unstabilized marine clay subgrade + optimized sub-base
2. Stabilized marine clay subgrade + optimized sub-base
3. Reinforced sections using:

- Geogrid
- RRCM (at the same interface)

1) Layer Preparation

- Subgrade compacted to 95% MDD
- Sub-base compacted to its optimum density
- Reinforcement layer placed at subgrade–sub-base interface
- Loading plate positioned at top surface

2) Loading Arrangement

A hydraulic loading frame was used to apply incremental static loads. The load was applied through a rigid circular plate, and the following measurements were recorded:

- Load–settlement response
- Elastic deformation characteristics
- Ultimate load capacity

3) Stress Measurement

Pressure cells installed at the subgrade–sub-base interface measured:

- Vertical stress distribution
- Reduction in stress due to reinforcement
- Effect of stabilization on interface pressure

F. Numerical Simulation

PLAXIS 2D was used to validate model pavement results. Soil parameters obtained from laboratory tests were used for constitutive modelling under axisymmetric loading conditions. Responses such as settlement, stress distribution, and deformation patterns were compared with experimental findings.

Table - 3: Basic properties of marine clay

S.No.	Parameters	Value
1	Specific gravity	2.5
2	Liquid limit (%)	80
3	Plastic limit (%)	35
4	Plasticity Index (%)	45
5	Shrinkage limit(%)	22.35
6	Sand (%)	3.9
7	Silt + Clay (%)	96.1 (47.1+49)
8	Unified Soil Classification	CH
9	Soil specification as per AASHTO	A-7-5
10	Optimum moisture content (%)	31
11	Maximum dry unit weight (kN/m3)	13.73
12	Unsoaked CBR(%)	4.54
13	Soaked CBR (%)	1.85
14	Free Swell Index(%)	150

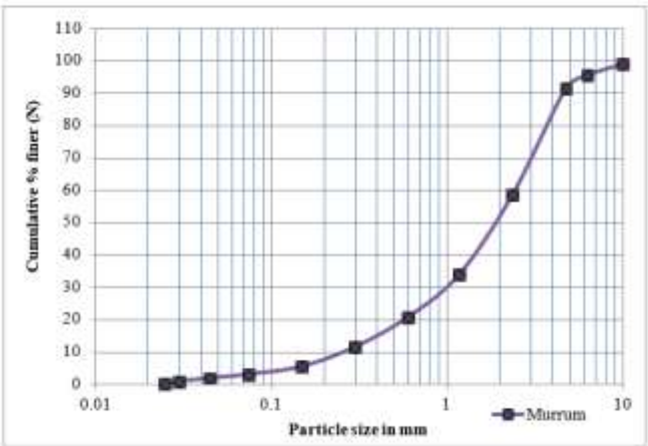

Fig - 1: Particle size distribution curve

Table - 4 Properties of marble dust

S.No.	Parameters	Value
1	Specific gravity	2.5
	Grain size distribution	
2	Sand sized particles (%)	74.72%
	Silt and clay sized particles (%)	25.28%
3	Maximum Dry Unit Weight (kN/m3)	18.87
4	Optimum Moisture Contents (%)	12.48%

5. RESULTS AND DISCUSSION

A. Preparation of Stabilized Soil Specimens

Marine clay was blended with selected industrial waste materials such as marble dust (MD), quarry dust (QD), fly ash (FA), and lime in predetermined proportions. Each mix was prepared through:

1. Dry mixing of soil and stabilizer
2. Addition of water to achieve optimum moisture content (OMC)
3. Thorough hand mixing for uniform distribution
4. Molding of samples for CBR, UCS, and compaction tests
5. Curing of samples where required (3, 7, and 14 days)

B. Compaction Characteristics

Standard Proctor compaction tests were performed to determine:

- Maximum Dry Density (MDD)
- Optimum Moisture Content (OMC)

The stabilized mixes generally exhibited:

- Increase in MDD with addition of MD and QD due to their granular and dense nature
- Decrease in OMC for MD- and QD-based mixes
- Slight increase in OMC for FA- and lime-added mixes due to pozzolanic reactions

These results indicate the beneficial densification effect of marble dust and quarry dust in stabilized subgrade applications.

C. Atterberg Limits

Plasticity index (PI) was evaluated to study the effect of admixtures on clay behavior.

- MD + Lime and QD + Lime combinations significantly reduced liquid limit and plasticity index
- Reduction in PI indicates improved workability and reduced swelling potential

The decrease in PI confirms the stabilizing action of lime and the filler effect of MD/QD.

D. Unconfined Compressive Strength (UCS) Tests

UCS tests were conducted on all stabilized mixes at:

- 0-day (immediate strength)
- 3-day curing
- 7-day curing
- 14-day curing

Observations

- UCS increased sharply with curing time for lime–industrial waste mixes due to pozzolanic reactions

- MD + 4% lime and QD + 6% lime exhibited the highest strength gains
- FA and GBFS blends exhibited moderate but continuous strength development

The improved UCS demonstrates enhanced bonding and formation of cementitious compounds (C–S–H and C–A–H gels).

E. California Bearing Ratio (CBR) Tests

Both soaked and unsoaked CBR tests were conducted.

Key Findings

- MD + Lime and QD + Lime mixes showed significant improvement in soaked CBR, confirming suitability for subgrade
- QD + 6% lime achieved maximum improvement (up to 460% increase compared to untreated clay)
- MD + 4% lime achieved moderate to high improvement
- FA–GBFS mixes showed high CBR values suitable for sub-base layers

Improved CBR values indicate higher load-carrying capacity and reduced deformation under wheel loads.

F. Triaxial Unconsolidated–Undrained (U–U) Test

U–U triaxial tests were performed to determine:

- Cohesion (c)
- Angle of internal friction (φ)
- Shear strength under undrained conditions

Results

- Stabilized mixes exhibited increased cohesion due to improved particle bonding
- QD-based mixes showed slight improvement in friction angle
- Lime-based mixes exhibited the highest increase in undrained shear strength

These results confirm that stabilization increases deformation resistance under rapid loading.

G. Elastic Modulus of Stabilized Mixes

The elastic modulus (E) was estimated using UCS values. The results showed:

- Significant improvement in stiffness for MD + Lime and QD + Lime mixes
- Moderate stiffness increase for FA–GBFS blends
- Higher modulus directly correlates with improved pavement performance

H. Selection of Optimum Stabilized Mixes

Based on laboratory performance:

- MD + 4% Lime
- QD + 6% Lime

were identified as optimum stabilized subgrade mixes, considering improvements in:

- CBR
- UCS
- Workability
- Compaction behavior
- Shear strength

These mixes were used in subsequent model pavement experiments.

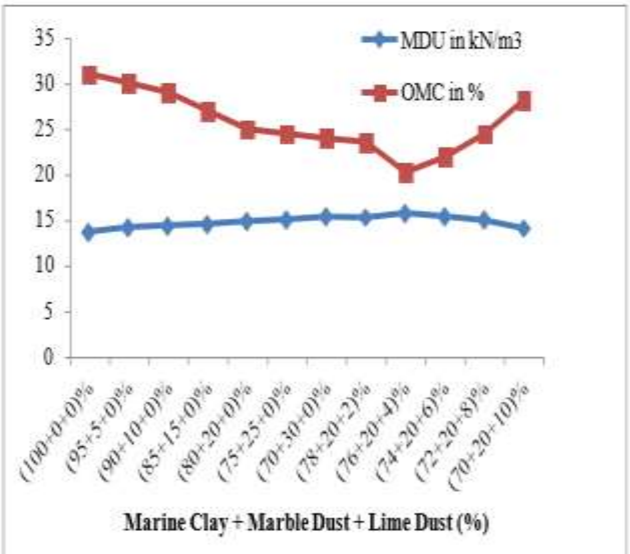

Fig - 2: Variation of MDU and OMC for marine clay stabilized with marble dust and lime

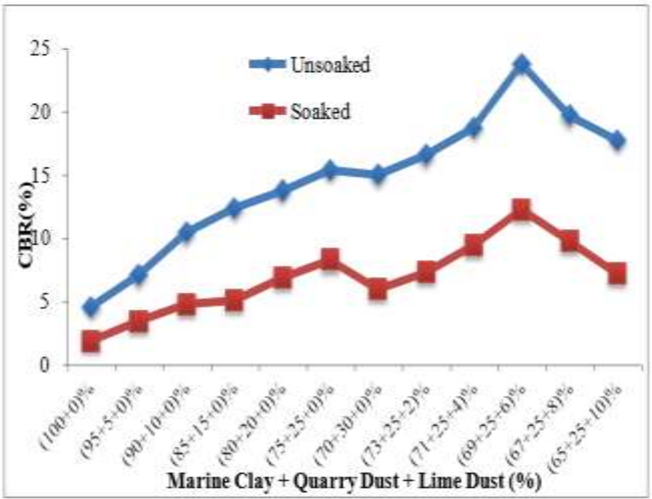

Fig- 3: Variation of soaked and un-soaked CBR for different proportions of QD and Lime

6. CONCLUSIONS

- Marine clay exhibits poor engineering properties, including high plasticity, low strength, and low CBR, making it unsuitable for pavement subgrades without stabilization.
- Industrial waste materials show strong potential for soil stabilization.
- Marble Dust (MD) and Quarry Dust (QD), when combined with lime, significantly improve the compaction, plasticity, and strength characteristics of marine clay.

- MD + 4% Lime and QD + 6% Lime provided the maximum improvement in performance.
- Soaked CBR values increased substantially for the optimized mixes:
- QD + 6% Lime improved soaked CBR by up to 460%,
- MD + 4% Lime achieved around 143% improvement, demonstrating their suitability for subgrade applications.
- UCS results indicate that curing enhances strength, confirming active pozzolanic reactions in lime-based and industrial waste mixes. QD + Lime and MD + Lime showed the highest UCS gain with 14-day curing.
- FA–GBFS sub-base mixes exhibited superior performance, showing high CBR, good compaction characteristics, and increased stiffness, making them suitable alternatives to conventional granular sub-base materials.
- Model pavement tests confirmed that reinforcement significantly enhances pavement performance.
- Geogrid reinforcement improved load distribution and reduced settlement.
- RRCM reinforcement provided even greater confinement, resulting in higher load-carrying capacity and lower interface stresses.
- Stress distribution analysis showed notable reductions in vertical stresses at the subgrade–sub-base interface for reinforced and stabilized systems, contributing to improved pavement durability.

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